

A vertical gray bar with a gradient, darker at the top and bottom, and lighter in the middle.

Summary of Run II Accelerator Physics Issues

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**Dept. of Energy Review of Accelerator Run II
October 28-31, 2002**

A vertical gray bar with a gradient, darker at the top and bottom, and lighter in the middle.



Accelerator Physics Issues for Run II

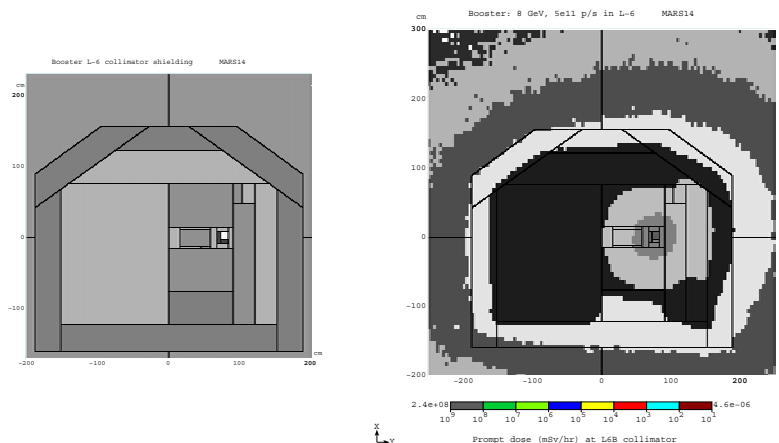
- **Interesting AP issues, many of which have been presented earlier:**
 - **Tevatron:** beam-beam, halo development and collimation, orbits & apertures, instabilities, lattice, etc.
 - **Main Injector:** emittance growth, injection match, coalescing, transition crossing, etc.
 - **Antiproton Source:** beam-gas, IBS, lattice, chromaticities, damping systems, etc.
 - **Proton Source:** space charge, injection, energy deposition, instabilities, etc.
 - **Recycler:** ...



Support from Beam Physics Department

- **Injectors, Recycler**
 - **Booster**
 - **Energy deposition calculations**
 - Beam loss and radiation studies, collimation system design and installation of primary and secondary collimators.

BOOSTER L-6 MARS MODEL AND DOSE



- **Injection Lambertson Magnet upgrade**
- **Space charge simulations (w/ P. Spentzouris, et al.)**
- **Transition crossing simulations**



Support from Beam Physics Dept. (cont'd)

- Main Injector -- Coalescing calculations; instabilities
- Recycler -- Injection, transfers; lattice issues; longitudinal calculations
- Support for Future Run II issues
 - Beam-beam
 - 132 nsec operation
 - Crossing angles, tune footprints, etc.
 - BB Δv compensation (electron lens)
 - Slip-stacking / barrier bucket
 - Electron cooling
- Other: NuMI, C0/Btev, LHC; FNPL; computing (BD unix cluster and parallel cluster admin.)
- Other projects (PD, LC, μ/ν) slowed down (essentially stopped), and efforts redirected toward Run II...



Physics Support for Run II

This talk will concentrate mostly on important Tevatron issues :

- Lattice efforts -- helical orbits, aperture, ...
- Beam-beam effects – tunes, dynamic aperture
- Longitudinal instabilities
- Energy deposition / backgrounds

Stages of a store:

- Proton only, central orbit and on helix
- Antiproton injection; cogging
- Ramping to high energy
- Collisions – initiation, HEP store



Luminosity Parameters

Luminosity given by:

$$L = \frac{3f_0 B N_p N_{\bar{p}} \gamma}{\beta^* \sqrt{(\epsilon_x^p + \epsilon_x^{\bar{p}})(\epsilon_y^p + \epsilon_y^{\bar{p}})}} \sqrt{\pi} \left(\frac{\beta^*}{\sigma_z} \right) e^{(\beta^*/\sigma_z)^2} [1 - \Phi(\beta^*/\sigma_z)]$$

or,

$$L = \frac{2f_0 \gamma}{\beta^* r_0} \frac{\xi_0 B N_{\bar{p}}}{(1 + \epsilon^{\bar{p}}/\epsilon^p)} \cdot H(\beta^*/\sigma_z)$$

ξ_0 = beam-beam parameter ~ 0.01 ;
 r_0 = classical radius; H = hour-glass

Presesntly,

$$L = \frac{2(48 \cdot 10^3)(10^3)}{(35)(1.5 \cdot 10^{-16}) \text{cm}^2 \text{sec}} \frac{(0.5 \cdot 10^{-2})(80 \cdot 10^{10})}{1 + 1/2} \frac{3}{5}$$

$$= 3 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$$

Major Issues: beam-beam interaction; emittance preservation (transverse & longitudinal) \rightarrow transfers, beam instabilities, noise sources, etc.; *plus, lifetime, detector background*



Beam Behavior at Injection

- Emittance dilution occurs during transfer; transfer line tuning and Beam Line Tuners are helping
- Magnet Effects
 - Tunes, chromaticities, coupling – drift with time
 - Magnet measurements → feed-forward drift compensation
 - Resonance driving terms
 - “shuffling” in 1980’s generated low driving terms; later years, magnets shuffled according to quench characteristics; however, driving terms – while larger – are still small enough
- **Dynamic aperture** explored on central orbit, on helix, with large/small (coalesced/uncoalesced) momentum spread
- Transverse instabilities
 - Chromaticity studies, octupole studies attempted to cure
 - Transverse dampers helping now
- **Longitudinal instabilities – dancing bunches** (*more later*)



Apertures and Orbits...

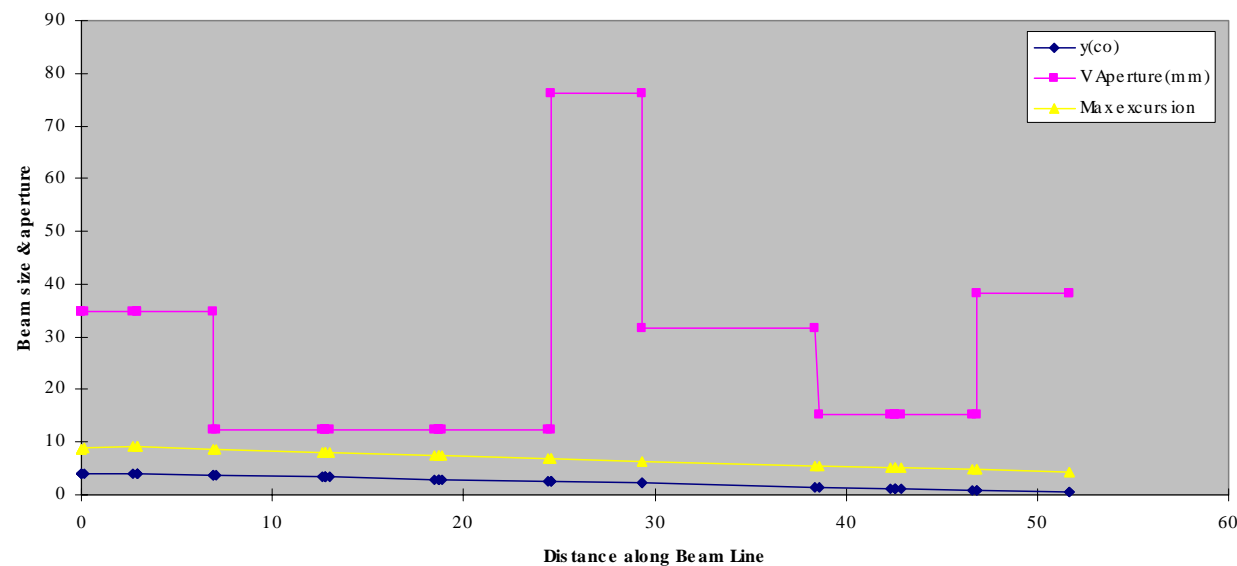
- To date: lifetimes at injection are dominated by physical aperture (C0 vertical aperture, in particular – few σ from beam centers)
- Helix at Injection
 - The original (design) (or, “new”) helix using 2 separators
 - Due to tight vertical aperture at C0, 4 separators used, producing the “new-new” helix
 - Investigating impact of increasing C0 aperture, and usefulness of increasing the helix separation
 - Next aperture issue – A0 straight section
 - Also – gains to be made using 4 or more separators during injection/ramping?



C0 Aperture

C0 Vertical Aperture

Max excursion
= 3σ , @ 25π mm-mr



- Unnecessary “abort” Lambertsons generate small vertical aperture
 - helix adjusted (4 sep.’s rather than 2) from its design to produce small vertical separation at this location at injection
 - Lambertson nonlinearities studied; not an issue for operation (B. Erdelyi)



C0 Aperture (cont'd)

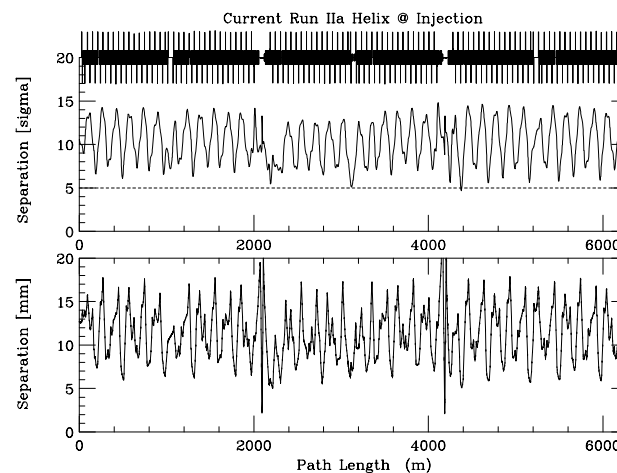
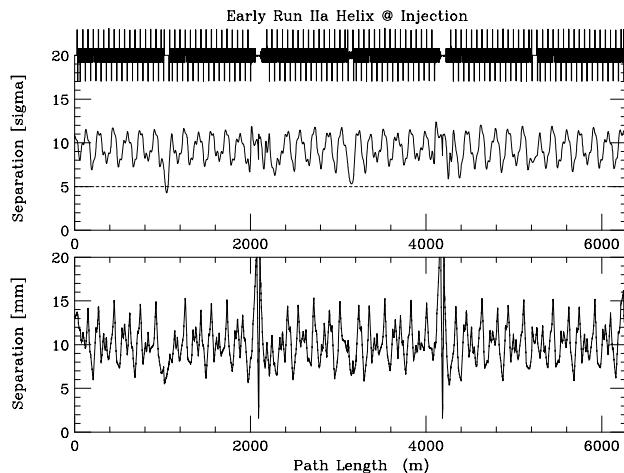
- **Options:**
 - Replace Lambertsons with warm MI dipole magnets
 - Reconfigure straight section with cryo magnets (as in other Tev straight sections)
 - Option for moving – but maintaining – synch-light monitor has been proposed (J. Johnstone)
 - Effects of nonlinearities of MI magnets have been analyzed (T. Sen) and are small
 - Gain from increased aperture...
 - allows for either
 - More room for larger emittance beams
 - Room to increase p-pbar separation
 - ...or both (mostly second option!)



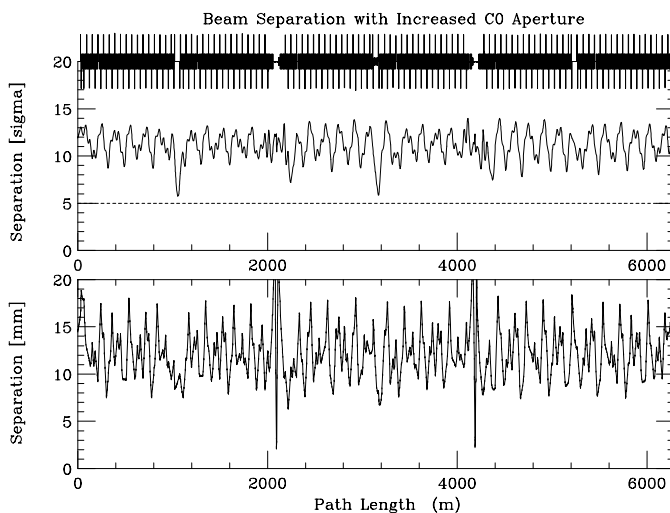
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C0 Aperture (cont'd) -- J. Johnstone



Plots start at F0



Current helix moves C0 separation to horizontal plane

Removing C0 restriction allows for larger overall separation

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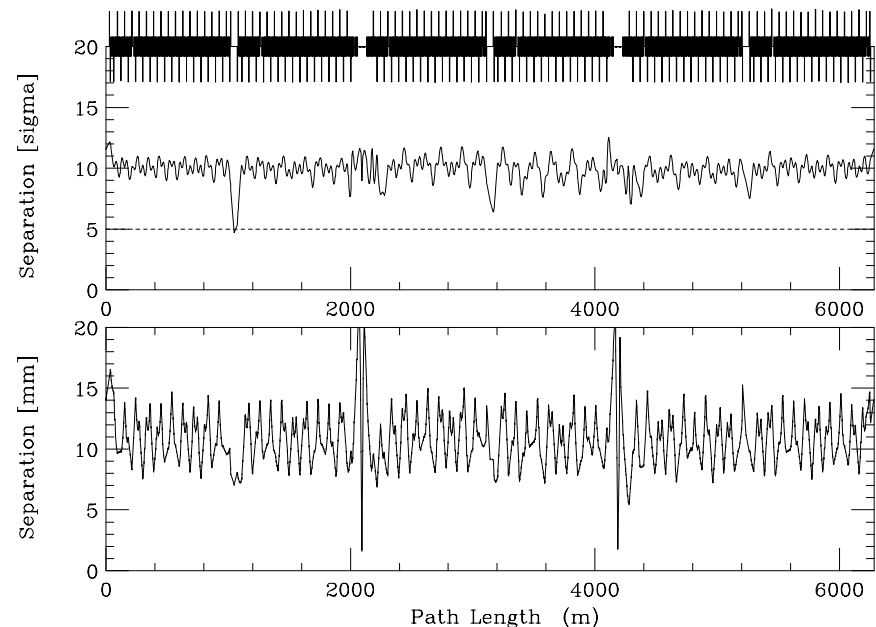


C0 Aperture (cont'd)

- If C0 vertical aperture restriction is removed, then can go back to the original design helix, giving smaller variations of beam separation around the ring
- Can also consider other helix schemes for injection
 - Consider using more than 2 separators during injection with the increased aperture; area of present studies

Helical orbit at 150 GeV using 8 separators (J. Johnstone).

Minimum separation (outside of A0,C0) is 8σ , average is 10σ .





Next: A0 Optics

- With C0 vertical aperture restriction removed, and original design helix restored, the closest approach of the two beams (in units of beam size) occurs in A0 region – “high beta” optics used for slow resonant extraction
- Thus, consider changing A0 optics to the original “standard” Collins straight section
- Work on-going to investigate C0 and A0 options; decisions tied to timing of long shutdown and scheduling/manpower issues for implementation in the tunnel

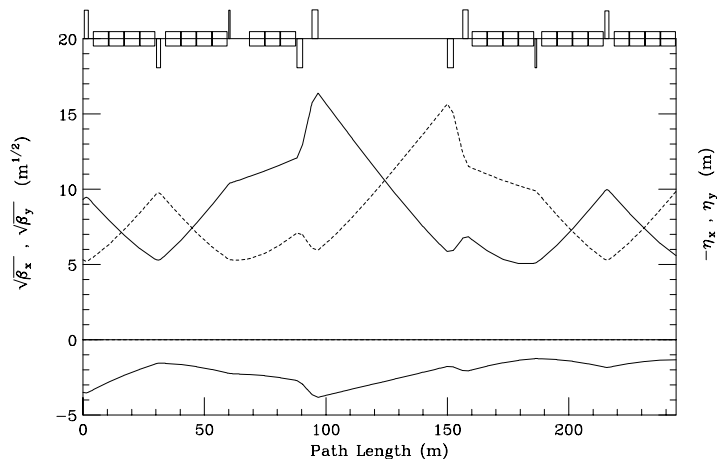


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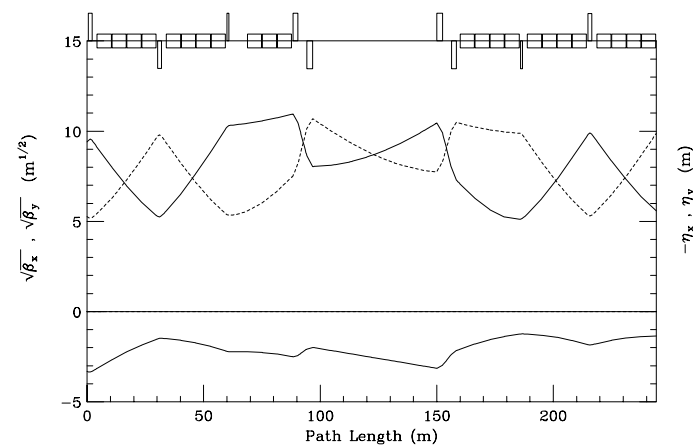
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A0 Optics and Helical Orbit

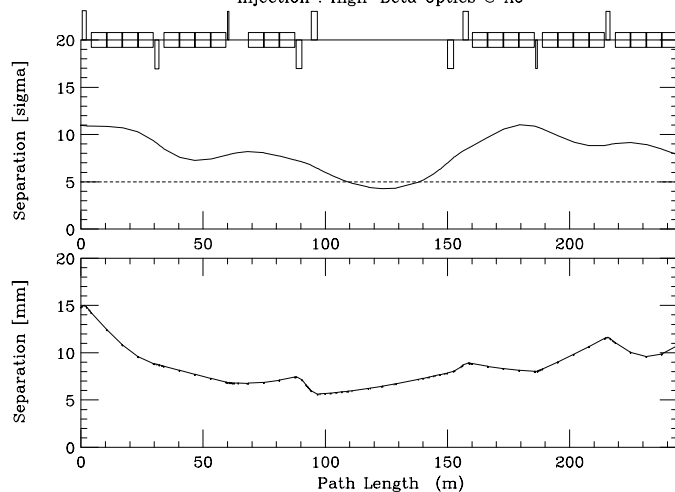
High-Beta Optics @ A0



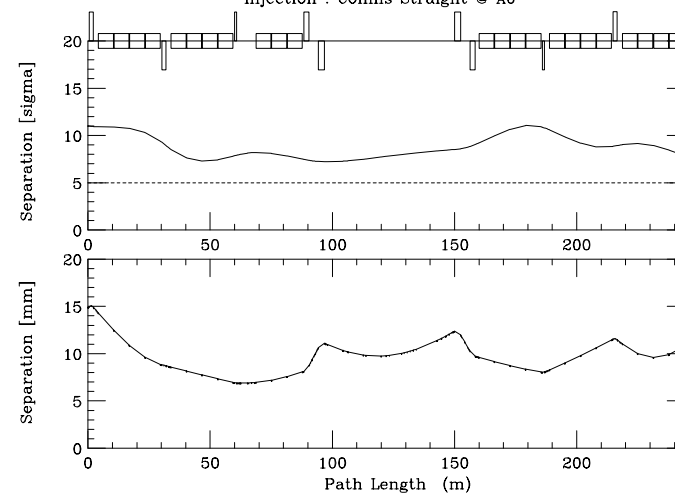
Design Straight Section



Injection : High-Beta Optics @ A0



Injection : Collins Straight @ A0



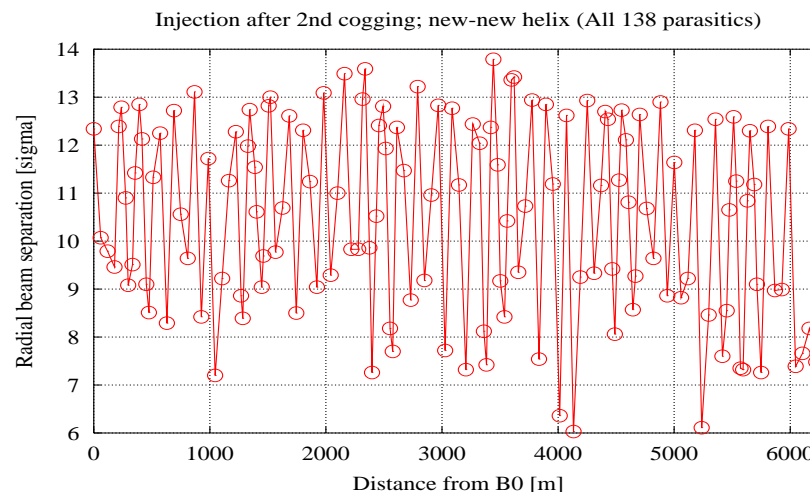
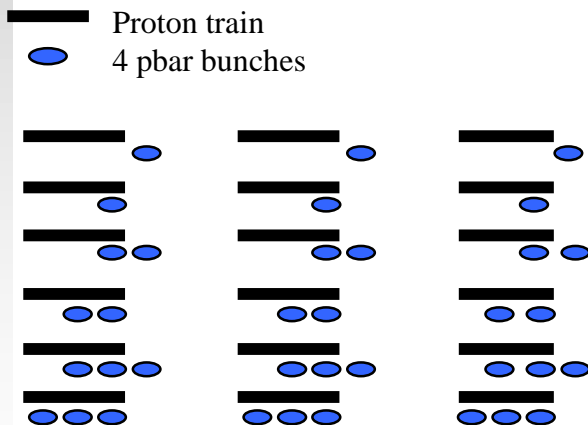
Courtesy
J. Johnstone

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Cogging Stages

- Three cogging stages as inject antiprotons into Tevatron
- At each stage, lifetimes correlated with antiproton emittance, and depends upon bunch number
- **Dynamic aperture calculations** carried out
- Also observed:
 - Proton lifetime changes during antiproton injection; do the “weak” pbars influence the “strong” protons?

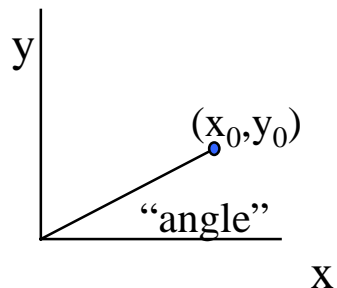
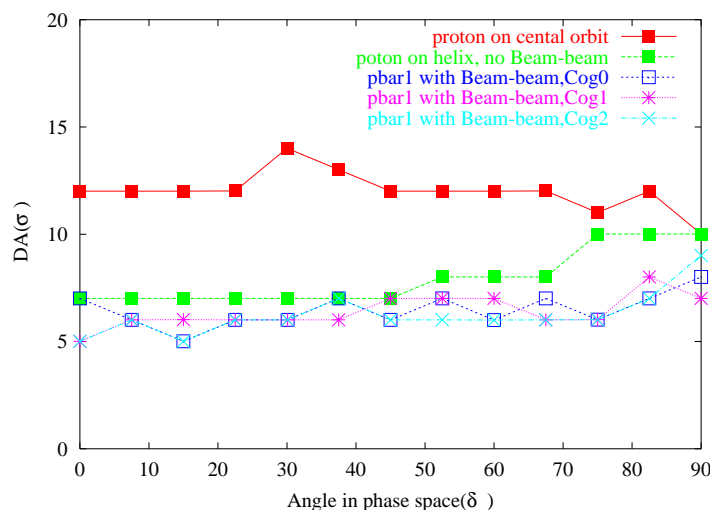




Injection Dynamic Aperture Calculations (M. Xiao)

Pre/Early-Run studies

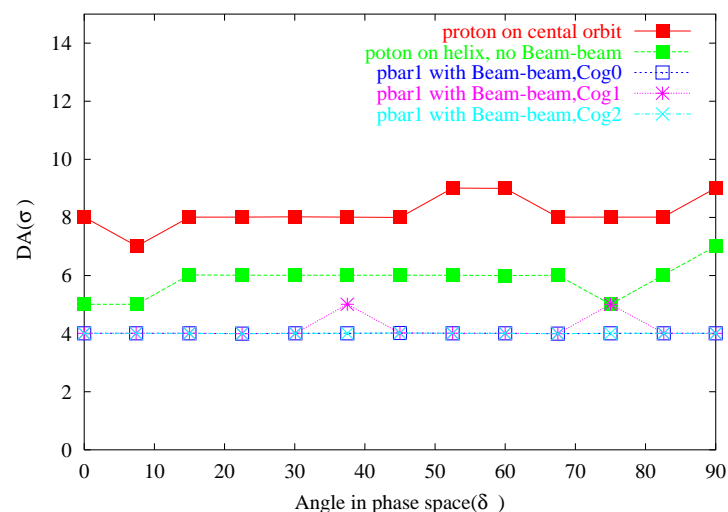
15π emittance, $dp/p=0.4e-4$ (1σ),
 $v_{x,y}=(0.585,0.575)$, Original helix



Starting at B0, center of
beam - beam kick; 10^5 turns

Present Conditions

25π emittance, $dp/p=13e-4$ (3σ),
 $v_{x,y}=(0.583,0.575)$, "new-new" helix



Behavior on/off helix
consistent with DA
calculations

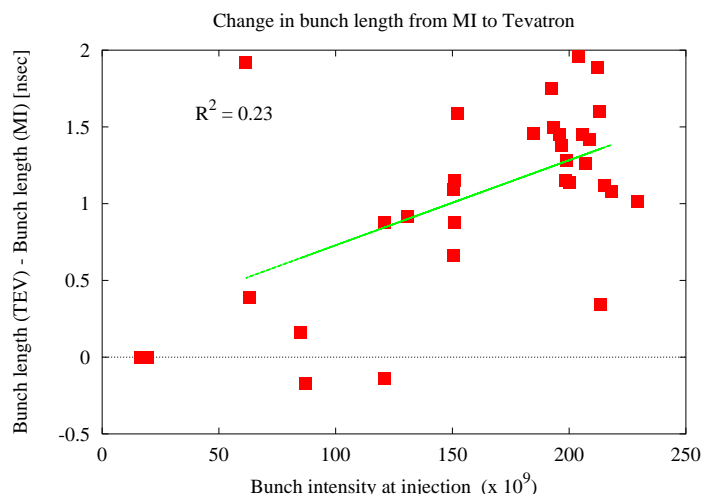


Ramping to High Energy

- Tunes, chromaticity and coupling wandered during start of ramp; snap-back algorithms tuned, improvements made
- Losses through the Ramp (T. Sen, F. Schmidt, et al.)
 - Study performed with 36 proton (only) bunches, with different characteristics
 - Varied -- momentum spread (coalescing), emittances (scraping), intensities (Booster turns)
 - Measured over time: intensities, emittances, ramp efficiencies, lifetimes at 150 GeV, etc.
 - Strong correlation of ramp efficiency with bunch length --> longitudinal scraping

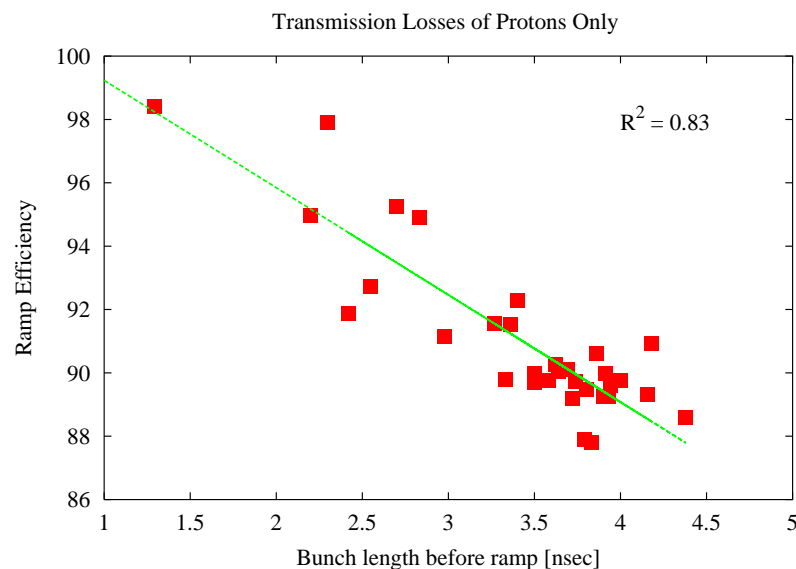


Losses through the Ramp (T. Sen, F. Schmidt)



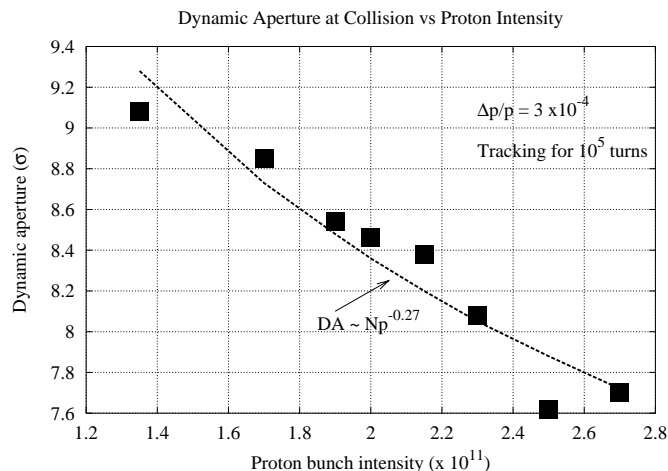
Main Injector bunch length at 150 GeV is ~2.5 nsec; increases by ~1-2 nsec upon injection into Tevatron

- Ramping efficiency worse for longer bunch lengths
- If could be preserved, would give 1.5 nsec (rms) bunches at 980 GeV, rather than 2.2 nsec
→ +16% gain in luminosity (hour glass)





Collisions at High Energy

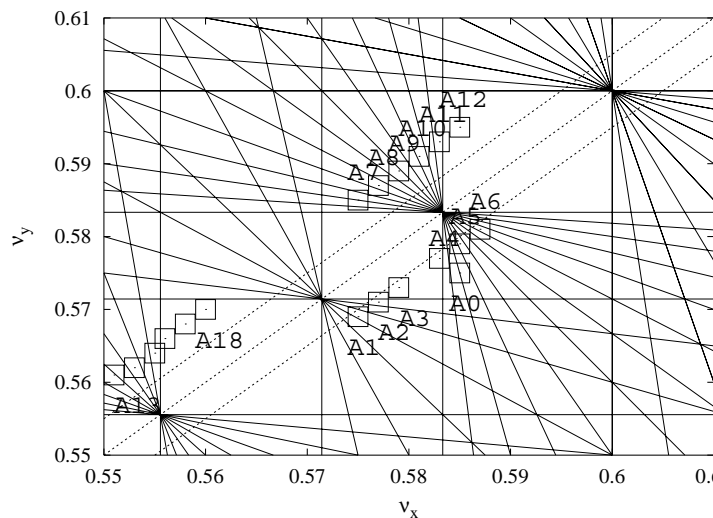


980 GeV Dynamic Aperture (Sen, Xiao)

Have calculated effects on pbars due to proton bunch intensity, tunes, etc., ...

← Prediction for higher intensities; awaiting verification...

Tracking results:

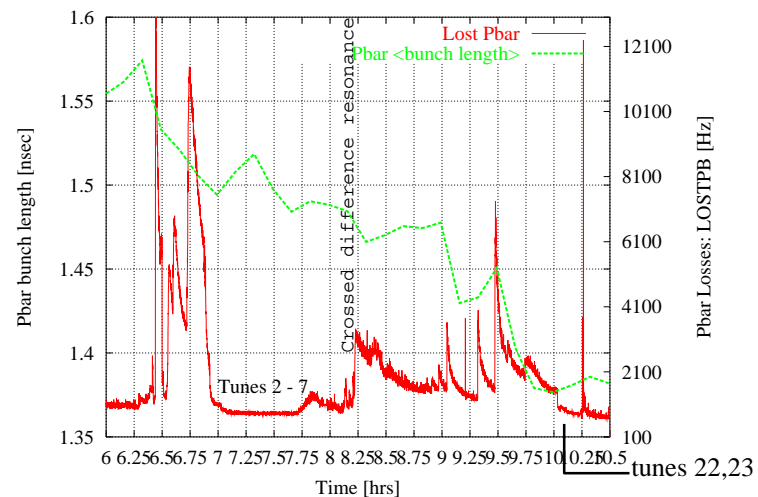
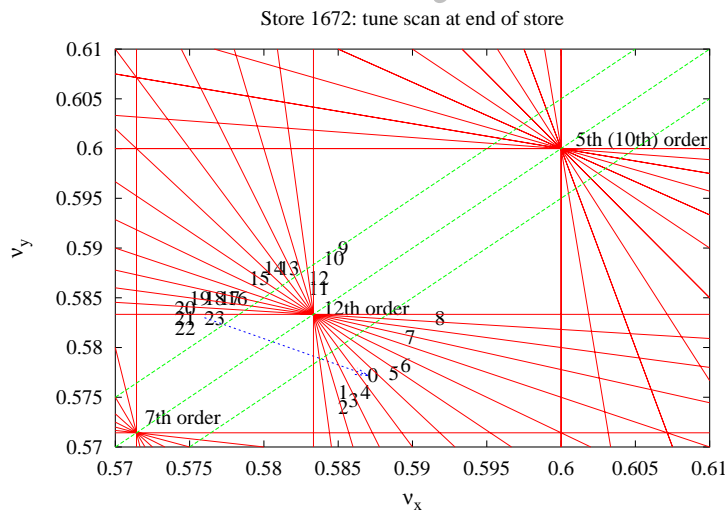


	Bare tunes	4D DA ($\langle DA \rangle$, DA_{min})	6D DA ($\delta_p = 3 \times 10^{-4}$) ($\langle DA \rangle$, DA_{min})
A0	0.585, 0.575	(10.0, 9.0)	(7.8, 6.0)
A1	0.575, 0.569	(9.2, 7.0)	(5.1, 4.0)
A2	0.577, 0.571	(9.3, 8.0)	(7.5, 6.0)
A3	0.579, 0.573	(9.4, 9.0)	(8.1, 7.0)
A4	0.583, 0.577	(9.8, 9.0)	(7.6, 6.0)
A5	0.585, 0.579	(9.6, 8.0)	(7.5, 7.0)
A6	0.587, 0.581	(9.5, 8.0)	(7.5, 6.0)
A7	0.575, 0.585	(11.0, 9.0)	(8.6, 7.0)
A8	0.577, 0.587	(10.7, 9.0)	(8.4, 8.0)
A9	0.579, 0.589	(10.5, 9.0)	(7.6, 5.0)
A10	0.581, 0.591	(10.0, 8.0)	(7.0, 5.0)
A11	0.583, 0.593	(9.5, 6.0)	(4.8, 3.0)
A12	0.585, 0.595	(8.5, 6.0)	(1.9, 1.0)
A13	0.551, 0.561	(10.9, 9.0)	(7.2, 5.0)
A14	0.553, 0.562	(10.7, 9.0)	(6.2, 5.0)
A15	0.555, 0.564	(10.2, 9.0)	(7.2, 6.0)
A16	0.556, 0.566	(9.9, 8.0)	(5.7, 3.0)
A17	0.558, 0.568	(11.0, 9.0)	(5.4, 3.0)
A18	0.560, 0.570	(10.5, 8.0)	(5.4, 3.0)

Table 7: Dynamic aperture, both 4D and 6D, calculated after 10^5 turns at different tunes shown in Figure 18. All beam-beam interactions were included. A0 is the nominal tune, A1, A2, A17 and A18 are close to 7th order resonances while A12 is close to 5th order resonances. We observe that at tunes away from these low order resonances the dynamic aperture does not change significantly.



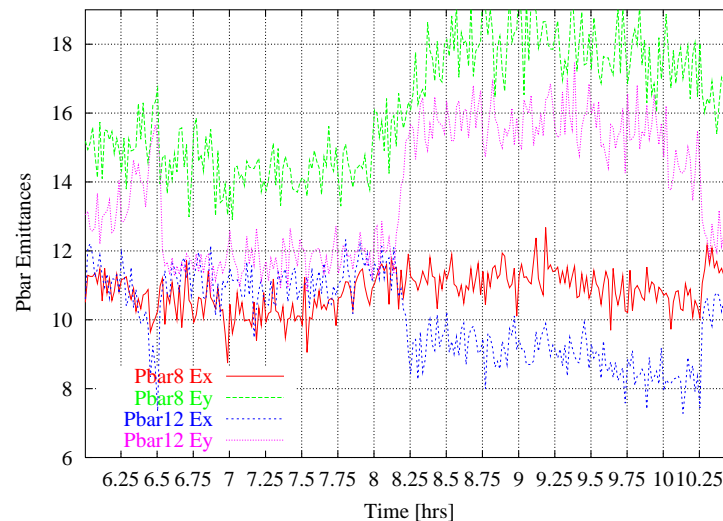
980 GeV Dynamic Aperture (T. Sen, M. Xiao)



Compare with experiment ...

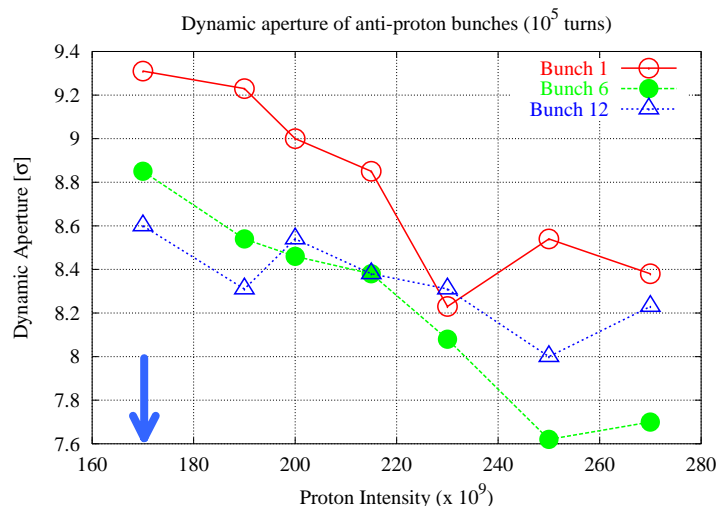
- Effects on losses, lifetimes qualitatively agree with dynamic aperture calculations
- Pbar bunch 12 has better lifetime; bunch 8 is worse
- Emittance exchange observed as crossing coupling resonance (pbars); not seen for protons

Tracking studies can aid in determining good working points



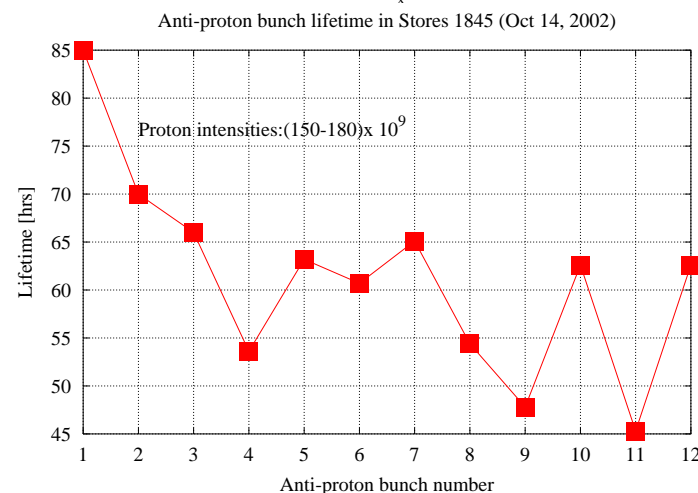
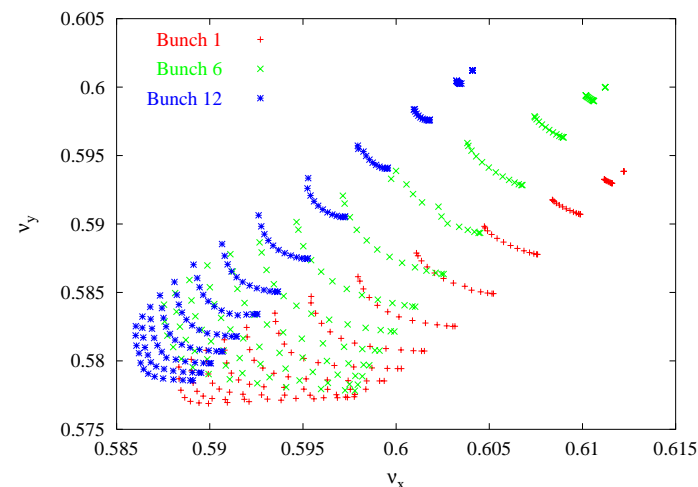


Pbar Dynamic Aperture



Typical store (right) shows bunch lifetimes higher for bunches with larger calculated dynamic apertures (above).

Note: D.A. predicted to decrease with increased bunch intensity...





IR Coupling Investigations ...

- **Transverse Coupling in IR's** (B. Erdelyi, et al.)
 - Wish to understand IR optics – CDF, D0 estimate that $\beta^* \sim 41$ cm, 43 cm, respectively (should be 35 cm)
 - Was issue in Run I -- rolled triplet quads (~8 mrad!)
 - Studies performed on B0 (CDF) region over three study periods; still to do: D0 region
 - Assume design model in region for computing transfer matrices, but rolled triplet magnets allowed; influence of detector magnets neglected
 - H&V BPM measurements made of responses to local orbit distortions through region; 64 orbit measurement produced $64 \times 4 = 256$ equations in 3 variables (for each triplet)
 - IR's have local skew quads; measurements made with these magnets both on and off.



IR coupling investigations ...

- **Transverse Coupling in IR's -- results for B0 (CDF)**
 - Roll angles obtained (linear fitting procedure):

Quadrupole	All data	Skew quads off	Recent Meas.
Q2F	-0.18	-0.17	0.34
Q3D	0.07	0.06	-0.07
Q4F	0.27	0.24	0.43
Q4D	0.51	0.49	0.43
Q3F	0.25	0.25	-0.04
Q2D	-0.02	-0.01	0.21

Promising method; T-B-T BPM system would greatly increase resolution of the method

Will continue for D0, perhaps other regions of the Tevatron



Lattice investigations ...

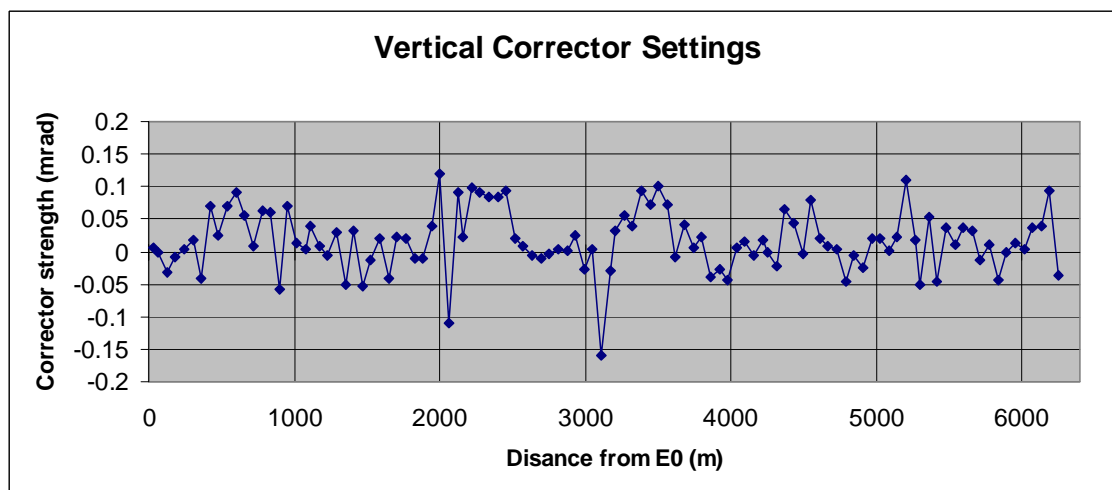
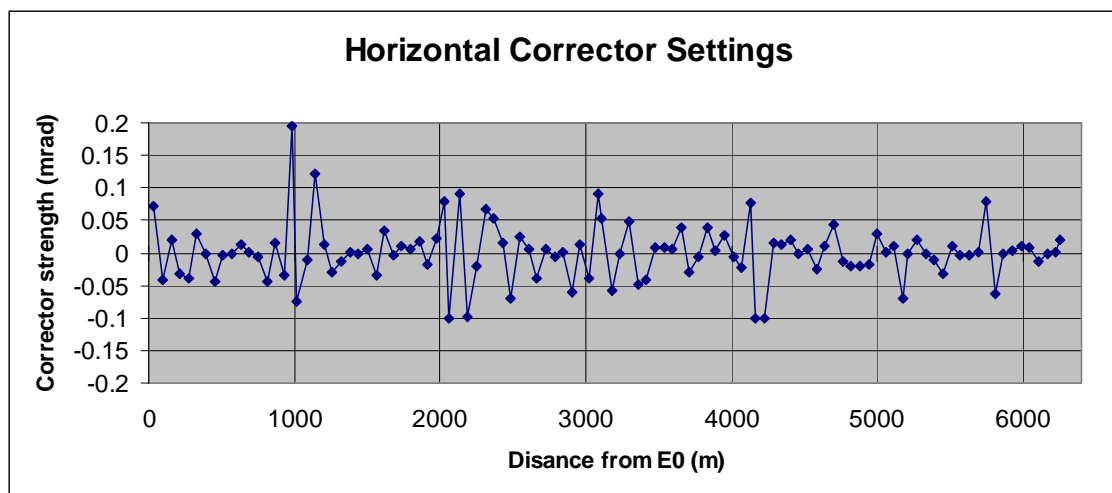
- While CDF “roll” looks OK, x-y coupling correction is higher than during previous run (N. Gelfand, et al.)
 - When tuned to be uncoupled, and skew quad circuits turned off, $\Delta v_{\min} \sim 0.2$
 - Models, using operational currents, do not agree with observation (by large factors)– unknown source(s) of coupling
 - Observation: vertical dipole correctors in E-F-A sectors have large average offsets
 - Around ring, $\langle \theta_y \rangle = 16 \mu\text{rad}$; $\langle \theta_x \rangle = 0.7 \mu\text{rad}$
 - Through portions of E-F-A, $\langle \theta_y \rangle = 80 \mu\text{rad}$ seen
 - Alignment measurements in above regions show rolls of 2-8 mrad (worse in dipoles than in quads); appears to change over time
 - Plan to do beam-based measurements of these regions, as in IR studies, to look for coupling sources



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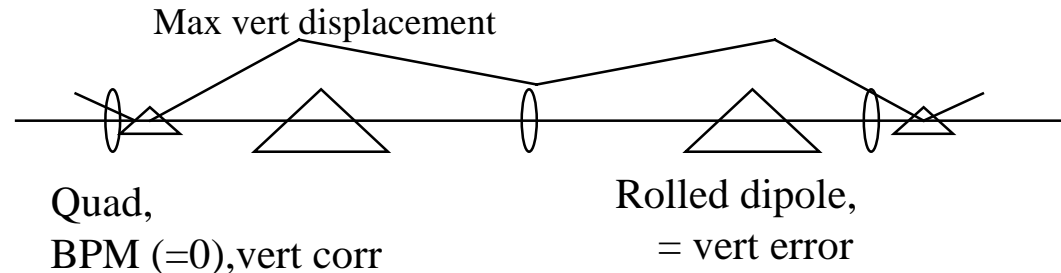
Tevatron Dipole Correctors



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Lattice investigations ...



- **Systematic offset in magnets due to rolls and corrections:**
 - **Rolled quads – linear coupling**
 - **Systematically rolled dipoles, corrected by vertical steering magnets –**
 - **“Scalloped” orbit through the dipole magnets**
 - **Generates ~1-2 mm vertical offsets through dipoles**
 - Therefore, more coupling due to b_2 feed-down; small, but noticeable
 - Other nonlinear effects?
 - **Being investigated further...**

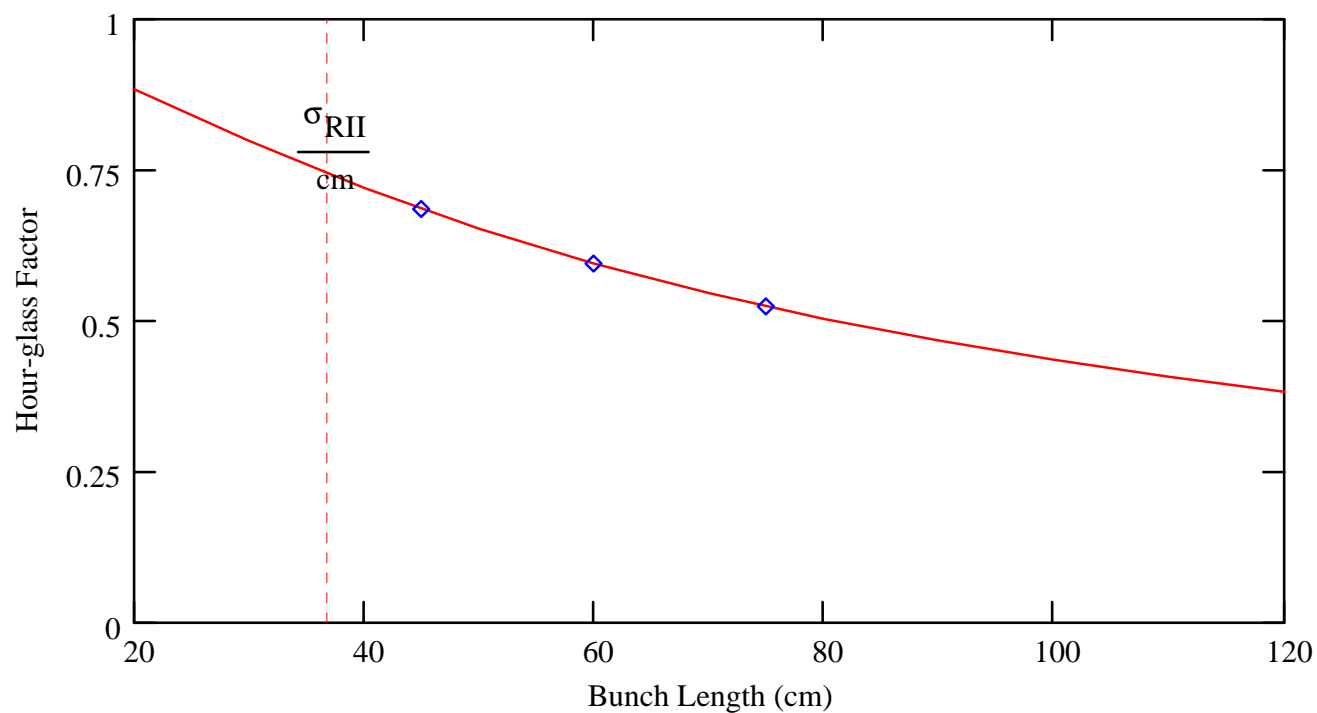


Longitudinal Issues

- Bunch length growth at 150 GeV
- Losses during the Ramp
- Beam instabilities – dancing bunches
- DC beam generation during store
- Effects –
 - Hour-glass effect: $\beta(s) = \beta^* + s^2/\beta^*$
 - since $\sigma_z > \beta^*$ -- > makes a hit on luminosity
 - Dispersion mismatches \rightarrow transverse emittance growth during transfers (observed effect)
 - Larger beam size \rightarrow larger beam-beam separation
$$\sqrt{(24\pi)(100)/(160 \cdot 6\pi)} \text{ mm} = 1.6 \text{ mm} \qquad (4\text{m})(0.7 \times 10^{-3}) = 2.8 \text{ mm}$$
 - Vertical dispersion in Tevatron – affecting luminosity? (probably not; should be small effect)



Hour-glass effect



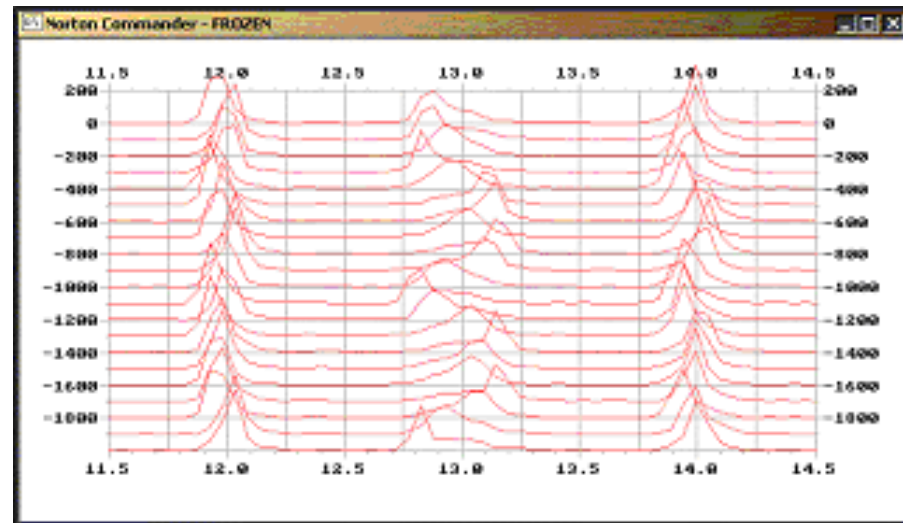
Presently operate around 60 cm (~2 nsec)



Instabilities -- Dancing Bunches

- Long-term coherent synchrotron oscillations of proton bunches observed in Tevatron, no damping of oscillations, no increase in emittance
- Not seen since longitudinal dampers commissioned; will return?? Would like to understand source...

Mountain range plot of uncoalesced bunches dancing in the Tevatron, July 2002; here, 3 from a train of ~30; courtesy R. Moore.





Dancing bunches

- Charge distribution different for coalesced / uncoalesced bunches; bunches oscillate at differing frequencies
- So far, uncoalesced data studied in detail
- Purely inductive impedance + a narrow rf cavity mode \rightarrow a modified Keil-Schnell criterion (Balbekov, Ivanov, 1991) -- yields $|Z/n|_{\text{thresh}}$ that can sustain such an oscillation
- For Tevatron, at $\sim 10^{10}$ /bunch, $Z/n \sim 2$ Ohm (numerically in right ball park)
- Computer model...



Dancing bunches (V. Balbekov)

- Compute longitudinal density $\rho(\phi)$, assuming

$$\rho(\phi) = \frac{3\pi e N}{2\lambda\phi_0} \left(1 - \frac{(\phi - \phi_c)^2}{\phi_0^2} \right)$$

- Compute corresponding longitudinal electric field; gives equation of motion of the form:

$$\frac{d^2\phi}{dt^2} + \sin \phi = -\frac{Q}{\phi_0^3} (\phi - \phi_c) \quad (t \leftarrow t/T_s)$$

- For Tevatron, $Q = -6 \times 10^{-13} \text{ N (i Z/n[Ohm])}$



Dancing bunches

(V. Balbekov)

Linear approximation separates to give...

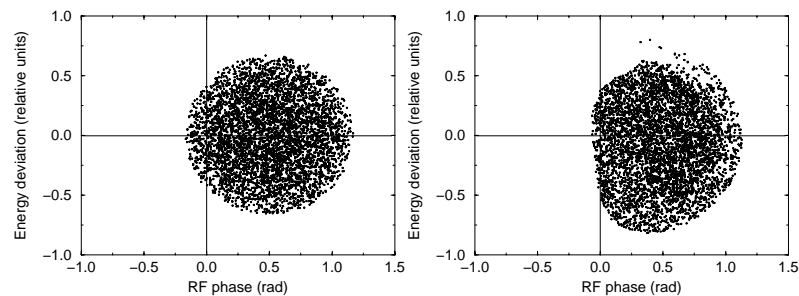
$$\frac{d^2 \phi_c}{dt^2} + \phi_c = 0$$

$$\frac{d^2 x}{dt^2} + \left(1 + \frac{Q}{\phi_0^3}\right)x = 0$$

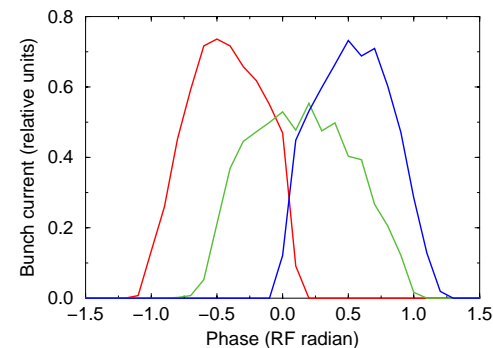
$$(x = \phi - \phi_c)$$

For $\phi_c = \text{const.}$, gives 2 frequencies;
mimics observations

Computer simulation:
5000 particles, $Q = -0.1$, $\phi_0 = 0.5$



Phase space in the beginning (left) / end (right).



Bunch form at interval 1/4 period of oscillations

Work continues...



DC Beam Generation

- **Develops immediately at injection, causing losses when ramp – full buckets at transfer**
- **But, also develops during store**
 - Mechanisms unknown; Tevatron Electron Lens (TEL) used as cure
- **Collaborative studies with experiments (A. Tollestrup, CDF, for example) -- sensitive measurements of DC beam migrating into abort gaps**
 - Indicates protons being lost from buckets at rate of several 10^6 /sec or so
 - Beam-Gas effects and subsequent loss rates are well understood



DC Beam Generation

- Phase noise, voltage noise most likely candidates; probably more sensitive to phase noise (motion near unstable fixed points)

- Random turn-to-turn phase jitter:

$$\frac{dS}{dt} = \frac{3}{2h} \sqrt{\frac{2\pi h |\eta| eV}{E}} eV \Delta\phi_{rms}^2 \quad dS/dt = 1 \text{ eV-sec/hour}$$

$$\rightarrow \Delta\phi_{rms} = 0.4^\circ \quad (\text{too big})$$

- Note: would also lead to 2π mm-mr/hour transverse emittance growth due to dispersion in cavities...

- Frequency spectrum: $d\phi^2/dt \sim 2\pi f_s^2 S_\phi(f_s)$

- $f_s \sim 36$ Hz @ 980 GeV for center of bunch; goes to 0 Hz at separatrix;
 $S_\phi(f_s) \sim 1.5 \times 10^{-9}$ rad²/Hz for observed growth rate
- possible mechanical vibration in cavities; produces similar spectral density; investigating (w/ Tev Dept, RF Dept, TD, ...)

- Possibly transverse modulation & synchro-betatron coupling:

- Motion of closed orbit due to varying transverse field gives changing path length ($\Delta C = D\Delta\theta$), and hence varying phase



DC Beam Generation

Numerical example: $5 \mu\text{rad}$ steering error (at $D=4\text{m}$) oscillating at 60 Hz (synchrotron frequency is 36 hz) can produce 0.5 degree phase oscillations of bunch center – particles near separatrix will leak out...

$$D = 4 \text{ m}$$

$$\theta_{\text{max}} = 5.615 \times 10^{-6}$$

$$f_m = 60 \text{ Hz}$$

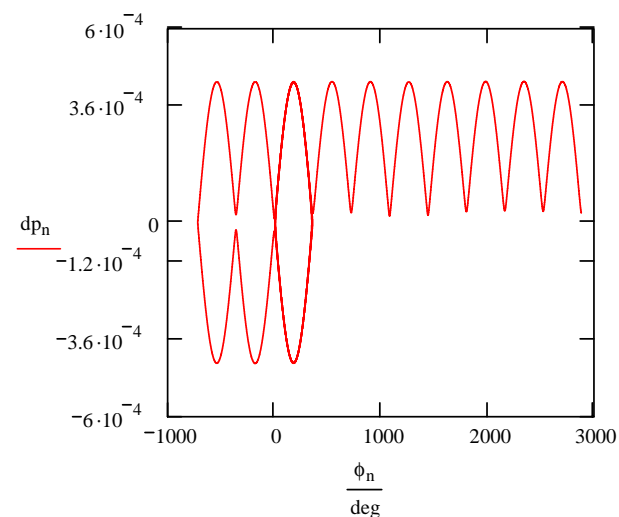
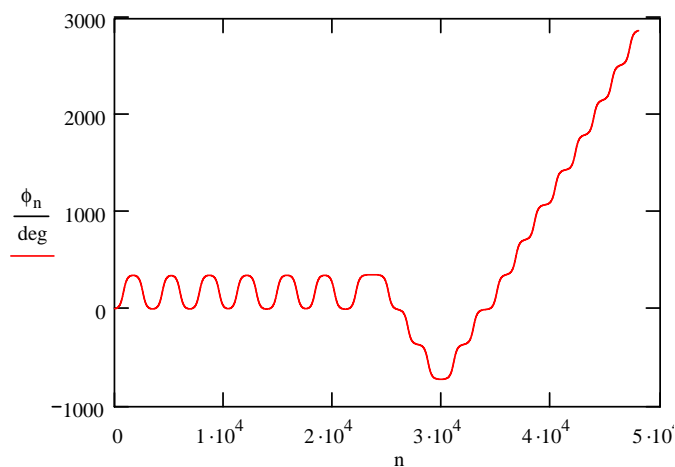
$$f_s = 35.638 \text{ Hz}$$

$$g_{\text{max}} = 0.752 \text{ deg}$$

Initial conditions:

$$\phi_0 - \pi = -170 \text{ deg} \quad dp_0 = 0$$

$$\max(\phi - \pi) = 2.697 \times 10^3 \text{ deg}$$



investigation continuing...



Energy Deposition (Mokhov, Drozhdin, et al.)

- Loss rates in B0 (especially) and D0 an issue
- Present system designed for cure of beam losses due to slow emittance growth – works well as designed; about 0.1% of particles escape system
- Large angle elastic scattering off residual gas nuclei and Coulomb scattering, between collimators and IPs, result in higher loss rates at detectors
- Detailed MARS model of A-sector, B0 and CDF (including Roman Pots) for beam loss and radiation studies -- suggests use of “shadow collimators”
 - 0.6 m “mask” just before last dipoles entering IP
 - $13\sigma_x$ and $20\sigma_y$ away from beam
 - Reduces backgrounds by about 10 times

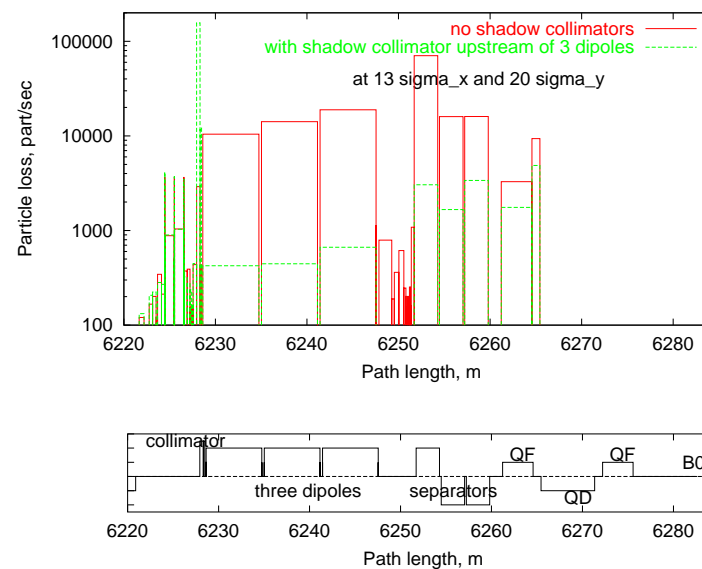
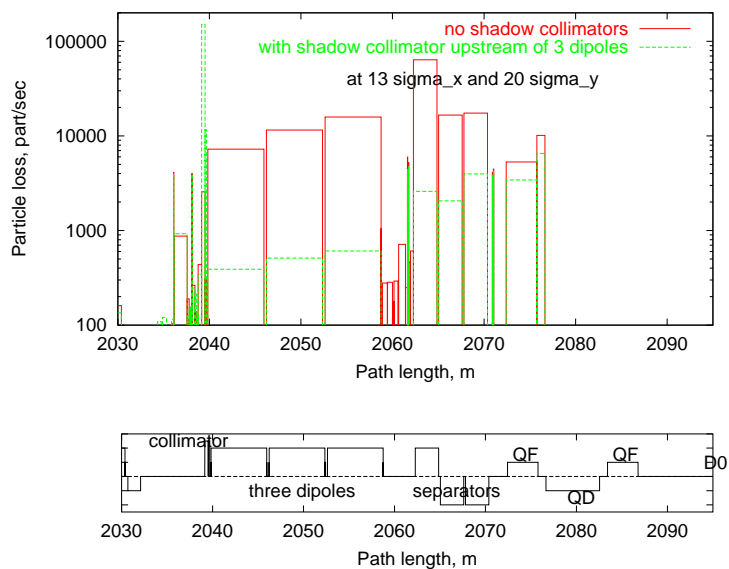


Fermi National Accelerator Laboratory

BEAM PHYSICS DEPARTMENT

Energy Deposition (Drozhdin)

0.6-M MASKS IN BØ and DØ



MJS/review Oct02



Collaborative Efforts

- **Collaborative Efforts**
 - **SLAC, LBNL -- Long-range beam-beam simulations, using particle-in-cell modeling**
 - Preliminary results, adding more physics (does not represent real situation yet)
 - **ORNL – Space charge calculations for Booster**
 - (also working w/ P. Spentzouris, et al., FNAL/PPD)
 - **UM, LBNL -- Recycler modeling, using MaryLie**
 - **CERN, BNL -- physicist exchange; F. Schmidt, W. Fisher, F. Pilat, V. Ptitsyn so far; more to come**
 - **ANL, IUCF -- AP groups meeting bi-monthly; so far, sharing computational / experimental experiences on instability issues**